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Mortality of Workers at a Nuclear Materials Production Plant at Oak Ridge, Tennessee, 1947-1990

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The Y-12 plant at Oak Ridge, Tennessee, produced nuclear materials for the U.S. government's nuclear weapons program beginning in 1943. Workers at Y-12 were exposed to low dose, internal, alpha radiation and external, penetrating radiation, as well as to beryllium, mercury, solvents, and other industrial agents. This paper presents updated results from a long-term mortality study of workers at Y-12 between 1947 and 1974, with follow-up of white men through 1990 and data reported for the first time for women and men of other races. Vital status was determined through searches of the National Death Index and other records, and the workers' mortality was compared to the national population's using standardized mortality ratios (SMRs). Total mortality was low for all Y-12 workers and total cancer mortality was as expected. Among the 6,591 white men, there were 20% more lung cancer deaths than expected (95% confidence interval [CI] 1.04–1.38). Death rates from brain cancer and several lymphopoietic system cancers were also elevated among white men, with SMRs of 1.28 and 1.46. Mortality from cancer of the pancreas, prostate, and kidney was similarly elevated. There was evidence of excess breast cancer among the 1,073 female workers (SMR 1.21, 95% CI 0.60–2.17). Lung cancer mortality among these workers warrants continued surveillance because of the link between internal alpha radiation exposure and this disease, but other agents, notably beryllium, also merit consideration as potential causes of lung cancer. Other cancers and agents should also be investigated as part of a comprehensive study of the health consequences of the production of nuclear weapons.

KEY WORDS: epidemiology, cancer, occupational health, ionizing radiation, beryllium, Oak Ridge, nuclear workers

INTRODUCTION

The Y-12 plant is part of a nuclear production and research complex at Oak Ridge, Tennessee, now controlled by the U.S. Department of Energy, but established during the second world war to support the federal government's development of nuclear weapons [Frome et al., 1990]. Workers at Y-12 were exposed to relatively low doses of internal, alpha radiation and external, penetrating radiation, as well as to beryllium, mercury, solvents, and other industrial agents.

Efforts to study the health of workers at Y-12 have focussed principally on determining the effects of ionizing radiation. The mortality experience of white men employed at Y-12 between 1947 and 1974 and followed through 1979 was last reported in 1988 [Checkoway et al., 1988]. Relative to the U.S. population, these workers had low mortality overall, but experienced a modest excess of mortality from lung cancer (standardized mortality ratio [SMR] 1.4, 95% confidence interval [CI] 1.1–1.7) and excesses of mortality

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from brain cancer and a group of other lymphopoietic system cancers (ICD-8 202, 203, and 208) that were somewhat larger in relative terms (SMR 1.8 and 1.9, respectively), but based on small numbers of deaths. Lung cancer mortality was quantitatively related to alpha and gamma radiation dose [Checkoway et al., 1988].

In this paper, we present the results of an ongoing mortality study of workers employed at Y-12 between 1947 and 1974, updating the follow-up of white men through 1990. In addition, we report for the first time on the mortality experience of women and non-white men employed at Y-12 between 1947 and 1974, who were omitted from the earlier report. Workers who were active at Y-12 between 1947 and 1974 but also had experience at the plant before 1947, when it produced enriched uranium (see below), were also excluded from the earlier report, and their mortality experience is considered here, as well.

MATERIALS AND METHODS

Plant History and Operation

The nuclear production plant now known as Y-12 began operation in 1943 under the management of Tennessee Eastman Corporation. The primary activity at this time was the production of enriched uranium (^{235}U) for atomic weapons, using an electromagnetic process of enrichment [Cragle et al., 1984]. In 1947, the Union Carbide Corporation assumed management of Y-12 on behalf of the government. The production of enriched uranium at the plant was discontinued, and its function shifted to research, fabrication, and assembly of nuclear materials for use in weapons, and the recycling of nuclear products and recovery from them of radioactive materials.

The production processes at Y-12 remained relatively constant after 1947. They involved the conversion of uranium hexafluoride (UF_6) to uranium tetrafluoride or "green salt" (UF_4), and its reduction in turn to uranium metal, which was fabricated into parts of various configurations. Wastes from the manufacturing and machining processes were recycled and the uranium was reused. Uranium wastes from other facilities were also recycled at Y-12.

Workers at Y-12 were exposed to beta and gamma radiations from external sources as well as internally exposed to alpha radiation from ^{235}U and ^{238}U, principally through the inhalation of uranium-bearing dusts [Polednak and Frome, 1986]. Other agents were also employed at Y-12, including solvents, machine oils, mercury, lead, and beryllium.

Population Definition and Follow-Up

The potentially eligible population was identified from a data base of approximately 420,000 employees of 18 Department of Energy (DOE) facilities maintained by the Center for Epidemiologic Research of Oak Ridge Associated Universities, Oak Ridge, Tennessee. This group included workers employed at least 30 days at Y-12 between January 1, 1947 and December 31, 1974. The latter date was dictated by the dates of the original study and has been maintained for consistency with other reports. Approximately 5,200 otherwise eligible workers for whom the data base indicated experience at other U.S. government nuclear installations, in addition to Y-12, were excluded in order to focus on conditions and exposures particular to Y-12 alone. However, those Y-12 workers with experience in the uranium enrichment plant operated at Y-12 by Tennessee Eastman between 1943 and 1947 were enumerated and separately analyzed to detect possible differences in the mortality of workers also employed during this early period.

The eligible group consisted of 10,620 workers. However, 23 with erroneous or missing employment or demographic information were excluded, leaving a cohort of 6,591 white men, 922 white women, 449 men and 149 women of African-American descent, and another 3 men and 2 women of other racial groups—8,116 workers in all—who had worked only at Y-12 in 1947 or later, when it produced fabricated metal products. Another 2,481 workers, including 1,764 white men, 562 white women, 85 African-American men, 69 African-American women, and 1 man of other race had also worked at Y-12 before 1947 when enriched uranium was produced, yielding a cohort of 10,597 workers in total.

Despite identical eligibility criteria, the membership of the present cohort of 6,591 white men with experience only at Y-12 after 1946 was not fully congruent with that of the cohort of 6,181 white men in the previous report on Y-12 [Checkoway et al., 1988]. This change was due to updates of the cohort rosters, with the merging of duplicate records for the same worker and deletion of workers initially listed as white males but later found to be female, in addition to the identification of more workers with experience at multiple nuclear installations.

The vital status of the population was determined from searches of the National Death Index, records of the Social Security Administration, the Health Care Financing Agency, the Tennessee Department of Motor Vehicles, a credit and pension benefits research group, as well as personnel and benefits records and obituaries. When access to Social Security records was discontinued in 1987, searching the National Death Index, which includes all deaths in the United States beginning in 1979, became the preferred method for updating vital status. The National Death Index has been shown to provide virtually complete ascertainment of deaths among men and among employed women [Boyle and Decouflé, 1990; Stampfer et al., 1984], so individuals known to be alive as of January 1, 1979 or later were assumed still alive at the end of the study if the National Death

TABLE I. Vital Status Ascertainment and Death Certificate Retrieval for Oak Ridge, Tennessee Y-12 Workers and Selected Subgroups as of December 31 1990

	Y-12 only, all workers		Y-12 only, white males		Y-12 only, non-white males		Y-12 only, all females	
Cohort	n	%	n	%	n	%	n	%
Vital status								
Alive	6,049	74.5	4,806	72.9	373	82.5	870	81.1
Deceased	1,861	22.9	1,729	26.2	58	12.8	74	6.9
Unknown	206	2.5	56	0.8	21	4.7	129	12.0
Total[a]	8,116	100	6,591	100	452	100	1,073	100
Percent of deaths with certificate	98.5		99.0		100.0		85.1	

[a]Percentages may not add to 100 because of rounding.

Index gave no indication they had died. Workers lost to follow-up earlier were assumed alive only to the date of last contact, usually their last day of employment.

For every worker with a death indication, the cause of death was ascertained through systematic searches for death certificates at all 52 vital statistics reporting units in the United States. Causes of death were coded by a qualified nosologist according to the International Classification of Diseases Adapted for Use in the United States (ICD), Eighth Revision.

Statistical Analysis

The mortality experience of Y-12 workers was compared to that of the U.S. population using a standard program for modified life table analysis to compute SMRs indirectly adjusted for age and calendar time [Monson, 1974]. Separate analyses were conducted for white men, non-white men, and women. Workers with experience at the Y-12 site during the period before 1947, when it produced enriched uranium, were considered separately from those who worked only in later years. In all analyses, only the underlying cause of death was considered, and the observation period for workers whose vital status was unknown at the end of the study was censored at the time they were last known alive.

RESULTS

Among the 8,116 men and women employed at Y-12 between 1947 and 1974, 74.5% were alive at the end of the study, 23% were deceased, and the vital status of 2.5% remained unknown. Within the cohort, there were differences by sex and ethnic group, with higher loss to follow-up among women and non-white men (Table I). In addition, the proportion of workers with death indications for whom death certificates could be obtained was notably lower for women (Table I).

The mortality experience of this group was somewhat more favorable than that of the U.S. population at large, and cancer mortality was equal to that of the general population (Table II). There were 202 deaths from lung cancer, resulting in an SMR of 1.17 (95% CI = 1.01–1.34). There were somewhat larger but still modest excesses of deaths from several less common cancers, including cancers of the pancreas, prostate, and kidney (Table II). Based on relatively small numbers of deaths, mortality from brain cancer and an aggregate group of lymphopoietic cancers not classified elsewhere (ICD 202, 203, and 208, hereinafter designated "other lymphatic cancers") was similarly elevated (SMRs of 1.29 and 1.32, respectively). There was no notable excess of mortality from any other cancer or from other causes except symptoms, senility, and ill-defined conditions (Table II).

All cause mortality among the 6,591 white males who worked at Y-12 in 1947 or later was modestly lower than that of the national population, and their mortality from all cancers was as expected (Table III). There was a 20% excess of deaths from lung cancer relative to the national population (95% CI = 1.04–1.38). As in the full cohort, there were also somewhat larger excesses of deaths from several less common cancers, including cancers of the pancreas (SMR = 1.32), prostate (SMR = 1.33), kidney (SMR = 1.39), and brain (SMR = 1.28). Mortality from the aggregate group of other lymphatic cancers was also in excess, with an SMR of 1.46.

Lung cancer mortality among white men was examined in detail to seek evidence of possible occupational causation (Table IV). Excess lung cancer mortality among this group was confined to those who began working at Y-12 between 1947 and 1954. However, the excess did not appear until a decade later, in the interval 1955–1964 (there was a deficit

TABLE II. Observed Deaths and Standardized Mortality Ratios (SMRs) for All Workers at the Oak Ridge, Tennessee Y-12 Nuclear Materials Plant, 1947–1990

Cause of death (ICDA code)[a]	Observed	SMR	95% CI[b]
All causes of death	1,861	0.88	0.84–0.92
All infective and parasitic disease (000–136)	9	0.38	0.17–0.72
All malignant neoplasms (140–209)	503	1.00	0.92–1.09
Cancer of			
Buccal cavity and pharynx (140–149)	3	0.21	0.04–0.62
Digestive organs and peritoneum (150–159)	106	0.85	0.70–1.03
Esophagus (150)	5	0.41	0.13–0.97
Stomach (151)	12	0.64	0.33–1.12
Large intestine (153)	39	0.89	0.63–1.22
Rectum (154)	6	0.54	0.20–1.18
Liver and gallbladder (155–156)	9	0.91	0.41–1.72
Pancreas (157)	34	1.36	0.94–1.90
Respiratory system (160–163)	209	1.15	1.00–1.32
Larynx (161)	5	0.75	0.24–1.76
Lung—primary and secondary (162)	202	1.17	1.01–1.34
Bone (170)	1	0.62	0.01–3.45
Skin (172–173)	11	1.07	0.54–1.92
Breast (females only) (174)	11	1.21	0.60–2.17
All female genital organs (180–184)	2	0.36	0.04–1.30
Prostate (185)	36	1.31	0.91–1.81
Testis (186–187)	0	0.00	0.00–1.59
Bladder (188)	8	0.72	0.31–1.42
Kidney (189)	16	1.30	0.74–2.11
Eye[c] (190)	0	0.00	0.00–10.62
Brain and other central nervous system (191–192)	20	1.29	0.79–2.00
Thyroid[c] (193)	0	0.00	0.00–4.01
All lymphopoietic cancer (200–209)	40	0.83	0.59–1.13
Lymphosarcoma and reticulosarcoma[c] (200)	4	0.50	0.14–1.29
Hodgkin's disease (201)	3	0.62	0.13–1.83
Leukemia and aleukemia (204–207)	11	0.60	0.30–1.07
Other lymphatic tissue[c] (202, 203, 208)	22	1.32	0.82–1.99
Benign neoplasms and neoplasms of unspecified nature (210–239)	5	0.79	0.26–1.85
Allergic, endocrine, metabolic, nutritional diseases[c] (240–279)	22	0.56	0.35–0.85
All diseases of blood and blood-forming organs (280–284)	6	1.23	0.45–2.68
Mental, psychoneurotic, and personality disorders[c] (290–317)	9	0.56	0.25–1.06
All diseases of nervous system and sense organs (320–389)	13	0.55	0.29–0.93
All diseases of circulatory system (390–458)	810	0.83	0.78–0.89
All respiratory diseases (460–519)	112	0.85	0.70–1.03
All diseases of digestive system (520–577)	61	0.60	0.46–0.77
All diseases of genitourinary system (580–629)	15	0.59	0.33–0.97
Chronic nephritis (582)	5	0.83	0.27–1.95
All diseases of the skin and cellular tissue (680–709)	0	0.00	0.00–2.02
All diseases of the bones and organs of movement (710–738)	1	0.23	0.00–1.30
Symptoms, senility, and ill-defined conditions (780–799)	72	2.71	2.12–3.42
All external causes of death (800–998)	193	0.86	0.74–0.99
All accidents (800–949)	120	0.85	0.70–1.01

[a]ICDA-8, International Classification of Diseases, adapted for use in the United States, 8th Revision.
[b]95% Confidence interval.
[c]Reference rates available only since 1950.

TABLE III. Observed Deaths and Standardized Mortality Ratios (SMRs) for White Male Workers at the Oak Ridge, Tennessee Y-12 Nuclear Materials Plant, 1947–1990

Cause of Death (ICDA code)[a]	Observed	SMR	95% CI[b]
All causes of death	1,729	0.91	0.86–0.95
All infective and parasitic disease (000–136)	8	0.40	0.17–0.78
All malignant neoplasms (140–209)	459	1.02	0.93–1.12
Cancer of			
Buccal cavity and pharynx (140–149)	3	0.23	0.05–0.68
Digestive organs and peritoneum (150–159)	93	0.83	0.67–1.02
Esophagus (150)	5	0.46	0.15–1.08
Stomach (151)	10	0.59	0.28–1.09
Large intestine (153)	33	0.84	0.58–1.17
Rectum (154)	6	0.59	0.22–1.29
Liver and gallbladder (155–156)	8	0.92	0.39–1.81
Pancreas (157)	30	1.32	0.89–1.88
Respiratory system (160–163)	201	1.19	1.03–1.36
Larynx (161)	5	0.81	0.26–1.88
Lung—primary and secondary (162)	194	1.20	1.04–1.38
Bone (170)	0	0.00	0.00–2.53
Skin (172–173)	11	1.16	0.58–2.07
Prostate (185)	35	1.33	0.92–1.85
Testis (186–187)	0	0.00	0.00–1.63
Bladder (188)	8	0.75	0.33–1.49
Kidney (189)	16	1.39	0.80–2.26
Eye[c] (190)	0	0.00	0.00–11.58
Brain and other central nervous system (191–192)	18	1.28	0.76–2.02
Thyroid[c] (193)	0	0.00	0.00–4.62
All lymphopoietic cancer (200–209)	39	0.90	0.64–1.22
Lymphosarcoma and reticulosarcoma[3] (200)	4	0.55	0.15–1.41
Hodgkin's disease (201)	3	0.69	0.14–2.01
Leukemia and aleukemia (204–207)	10	0.60	0.29–1.10
Other lymphatic tissue[c] (202,203,208)	22	1.46	0.92–2.22
Benign neoplasms and neoplasms of unspecified nature (210–239)	3	0.55	0.11–1.60
Allergic, endocrine, metabolic, nutritional diseases[c] (240–279)	21	0.62	0.38–0.95
All diseases of blood and blood-forming organs (280–284)	6	1.47	0.54–3.20
Mental, psychoneurotic, and personality disorders[c] (290–317)	9	0.67	0.31–1.27
All diseases of nervous system and sense organs (320–389)	13	0.62	0.33–1.06
All diseases of circulatory system (390–458)	777	0.87	0.81–0.93
All respiratory diseases (460–519)	106	0.88	0.72–1.07
All diseases of digestive system (520–577)	56	0.62	0.47–0.80
All diseases of genitourinary system (580–629)	12	0.55	0.28–0.96
Chronic nephritis (582)	5	0.97	0.31–2.27
All diseases of the skin and cellular tissue (680–709)	0	0.00	0.00–2.50
All diseases of the bones and organs of movement (710–738)	1	0.29	0.00–1.61
Symptoms, senility, and ill-defined conditions (780–799)	66	2.93	2.27–3.73
All external causes of death (800–998)	174	0.89	0.76–1.03
All accidents (800–949)	109	0.86	0.71–1.04

[a]ICDA-8, International Classification of Diseases, adapted for use in the United States, 8th Revision.
[b]95% Confidence Interval.
[c]Reference rates available only since 1950.

TABLE IV. Lung Cancer Mortality of Oak Ridge, Tennessee Y-12 Workers, 1947–1990, by Year of Hire, Latency (Time Since Hire), Duration of Employment, and Calendar Year at Risk

	Observed	SMR[a]
Calendar year of hire		
1947–1954	161	1.27
1955–1964	24	0.96
1964–1974	9	0.86
Latency (years)		
<10	10	1.19
10–19	39	1.28
20–29	78	1.30
≥30	67	1.07
Duration (years)		
<5	69	1.23
5–10	28	1.87
10–19	41	1.87
20–29	45	1.11
≥30	11	0.73
Calendar year at risk		
1947–1954	0	0.00
1955–1964	11	1.33
1965–1974	37	1.27
1975–1979	45	1.59
1980–1990	63	1.05

[a]SMR = Standardized mortality ratio.

of lung cancer at Y-12 initially), peaked in the late 1970s, and disappeared by close of follow-up in 1990. When duration of employment and latency were considered (Table IV), lung cancer mortality was greatest relative to the national population among men employed 5–20 years at Y-12 and with 10–30 years of follow-up since hire.

Death rates from all causes and from all cancers were considerably more favorable among the 1,073 women who worked at Y-12 in 1947 or later than among the U.S. female population (Table V). With only 31 cancer deaths in total among the women in the Y-12 workforce, the numbers of deaths from specific cancers were small and the SMRs imprecise. The largest proportion of cancer deaths were from breast cancer (11 deaths), with 21% more deaths than expected (95% CI = 0.6–2.2). Lung cancer mortality (five deaths) was lower than expected, and brain cancer and pancreatic cancer mortality (two deaths each) were higher.

Non-white men with post-1946 experience at Y-12 also had more favorable mortality experience than the national non-white population for all causes and all cancers (Table VI). This group was 99% African-American and very small, with only 452 men, so the SMRs for specific causes of death were imprecise. The largest proportion of cancer deaths was due to cancers of the digestive system and peritoneum (seven deaths), for which the SMR was greater than expected (SMR = 1.6). There was no excess of lung cancer, and there were too few deaths from other cancers for meaningful interpretation.

Addition of women and men who worked at the enrichment plant that existed at Y-12 before 1947, as well as subsequently, did not materially change the results for any cause of death. Among this expanded cohort of 10,597 workers, there were 316 deaths from lung cancer, with a modest excess relative to the national population (SMR = 1.17, 95% CI = 1.05–1.31). Excesses of brain cancer, lymphatic cancers other than lymphomas and leukemias, and pancreatic cancer similar in magnitude and precision to those among workers employed only after 1946 were also observed, but there was no noteworthy excess of deaths from any other cancer.

DISCUSSION

We considered the mortality experience through 1990 of several cohorts of workers at the Y-12 nuclear materials plant. White men with experience only at Y-12 in 1947 or later were the largest of all the cohorts considered, and their mortality experience consequently dominated when they were combined with other groups. White men experienced moderately lower death rates from all causes and diseases of the circulatory system than the national population, but essentially the same rate of mortality from cancer. These patterns are typical of industrial cohorts [Fox and Collier, 1976].

There were about 20% more lung cancer deaths than expected among white men based on the mortality of the national population. In absolute terms, this was equivalent to 46 excess lung cancer deaths between 1947 and 1990 among all 10,597 Y-12 workers. Death rates from brain cancer and an aggregate category of lymphopoietic system cancers other than lymphomas and specifically classifiable leukemias (ICD-8 202, 203, 208) were also elevated among white men and the larger cohorts which included them, with SMRs in the range of 1.2–1.5, as were mortality rates from cancer of the pancreas, prostate, and kidney. Including workers who had experience at the enrichment plant at Y-12 before 1947 did not change these patterns. The excesses of lung cancer, brain cancer, and other lymphopoietic cancers among white men are broadly consistent with previous observations of this population based on follow-up through 1979 [Checkoway et al., 1988].

Workers in production areas of the Y-12 plant had documented inhalation exposures to internally deposited alpha-emitting radionuclides, which are acknowledged as a cause of lung cancer [BEIR Committee, 1988]. External exposures to penetrating beta and gamma-radiations, which also occurred at Y-12, have also been associated with lung cancer [BEIR Committee, 1990]. A modest excess of lung can-

TABLE V. Observed Deaths and Standardized Mortality Ratios (SMRs) for Female Workers at the Oak Ridge, Tennessee Y-12 Nuclear Materials Plant, 1947–1990. Causes With No Deaths Omitted

Cause of death (ICDA code)[a]	Observed	SMR	95% CI[b]
All causes of death	74	0.63	0.49–0.79
All infective and parasitic disease (000–136)	1	0.60	0.01–3.33
All malignant neoplasms (140–209)	31	0.80	0.55–1.14
Cancer of			
Digestive organs and peritoneum (150–159)	6	0.76	0.28–1.66
Large intestine (153)	4	1.16	0.31–2.98
Pancreas (157)	2	1.27	0.14–4.59
Respiratory system (160–163)	5	0.76	0.24–1.77
Lung—primary and secondary (162)	5	0.78	0.25–1.82
Breast (174)	11	1.21	0.60–2.17
All genital organs (180–184)	2	0.36	0.04–1.30
Brain and other central nervous system (191–192)	2	1.82	0.20–6.59
All lymphopoietic cancer (200–209)	1	0.30	0.00–1.68
Leukemia and aleukemia (204–207)	1	0.79	0.01–4.41
All diseases of circulatory system (390–458)	17	0.40	0.23–0.63
All respiratory diseases (460–519)	1	0.16	0.00–0.88
All diseases of digestive system (520–577)	2	0.35	0.04–1.25
All diseases of genitourinary system (580–629)	2	1.00	0.11–3.62
Symptoms, senility, and ill-defined conditions (780–799)	2	1.30	0.15–4.71
All external causes of death (800–998)	6	0.62	0.23–1.35
All accidents (800–949)	5	0.87	0.28–2.03

[a]ICDA-8, International Classification of Diseases; adapted for use in the United States, 8th Revision.
[b]95% Confidence interval.

cer has also been observed among some subgroups of men who worked at the enrichment plant between 1943 and 1946 [Polednak and Frome, 1986; Cookfair et al., 1988; Frome et al., 1990] and among welders at several Oak Ridge facilities [Polednak, 1981]. Among the other agents present in the plant, beryllium is an established lung carcinogen [IARC, 1993; Steenland et al., 1995], but no estimates of exposure to beryllium or other chemical agents were available for the present study. Relative patterns of mortality among Y-12 workers monitored for exposure to mercury and those not monitored suggest that the excess of lung cancer mortality was not related to mercury, however [Cragle et al., 1984].

Examining temporal patterns of SMRs cannot replace analyses based on quantitative data for exposure to specific agents. Nevertheless, our observations in a detailed analysis of lung cancer among white men that the excess of lung cancer was largest among workers with 10–29 years latency and 5–19 years of employment are consistent with the epidemiological patterns that would be expected if an occupational lung carcinogen were involved. Excess risk was not associated with short-term employment (and presumably low cumulative exposures to occupational agents), and although workers with very long tenure had favorable mortality, this phenomenon is characteristic of industrial cohorts, presumably because the healthiest workers tend to remain employed the longest [Fox and Collier, 1976]. The 10–30 year range of latency associated with excess risk is also consistent with expectations for occupational lung carcinogens.

At Y-12, exposures to ionizing radiation were highest in the early years of the plant's operation, during a period of intensive weapons production. This temporal pattern of exposure may account for the presence of excess lung cancer risk exclusively among men who began work before 1955, as well as the peak and subsequent decline of lung cancer SMRs in the 1970s and 1980s. However, alternative explanations for the rise and fall of SMRs must also be considered, including noncausal ones. The proportion of the cohort with unknown vital status remained at 3% or less through 1989, but increased to 9% in 1990. Underascertainment of deaths in this single year is unlikely to account for the decline in observed lung cancer mortality since 1985.

The magnitudes of the SMRs for lung cancer are also modest enough that the observed excess mortality could, in principle, be due to confounding by tobacco smoking if Y-12 workers smoked more than the national population [Cornfield et al., 1959]. However, empirical data indicate that such differences in smoking practices are rare [Axelson

TABLE VI. Observed Deaths and Standardized Mortality Ratios (SMRs) for Causes of Death With One or More Deaths for Non-White Male Workers at the Oak Ridge, Tennessee Y-12 Nuclear Materials Plant, 1947–1990

Cause of death (ICDA code)[a]	Observed	SMR	95% CI[b]
All causes of death	58	0.67	0.51–0.87
All malignant neoplasms (140–209)	13	0.86	0.46–1.46
Cancer of			
Digestive organs and peritoneum (150–159)	7	1.63	0.65–3.36
Stomach (151)	2	2.34	0.26–8.46
Large intestine (153)	2	2.04	0.23–7.38
Liver and gallbladder (155–156)	1	2.11	0.03–11.75
Pancreas (157)	2	2.77	0.31–9.99
Respiratory system (160–163)	3	0.56	0.11–1.65
Lung—primary and secondary (162)	3	0.60	0.12–1.76
Bone (170)	1	18.12	0.24–100.83
Prostate (185)	1	0.83	0.01–4.59
Benign neoplasms and neoplasms of unspecified nature (210–239)	2	9.87	1.11–35.63
Allergic, endocrine, metabolic, nutritional diseases[c] (240–279)	1	0.52	0.01–2.91
All diseases of circulatory system (390–458)	16	0.55	0.31–0.89
All respiratory diseases (460–519)	5	1.11	0.36–2.59
All diseases of digestive system (520–577)	3	0.62	0.12–1.80
All diseases of genitourinary system (580–629)	1	0.60	0.01–3.34
Symptoms, senility, and ill-defined conditions (780–799)	4	1.61	0.43–4.11
All external causes of death (800–998)	13	0.66	0.35–1.12
All accidents (800–949)	6	0.65	0.24–1.41

[a]ICDA-8, International Classification of Diseases, adapted for use in the United States. 8th Revision.
[b]95% Confidence Interval.
[c]Reference rates available only since 1950.

and Steenland, 1988]. More directly, the lack of elevated mortality from other tobacco-related diseases, such as nonmalignant respiratory disease and heart disease, is evidence against the prevalence of smoking among Y-12 workers being high enough relative to the national population to produce noteworthy confounding.

High doses of ionizing radiation have been shown to increase the risk of brain cancer among laboratory animals and humans [BEIR Committee, 1990]. Excess mortality from brain cancer has also been reported at lower doses among workers at some nuclear facilities [Wilkinson et al., 1987; Hadjimichael et al., 1983], but, in general, epidemiological evidence that brain cancer has resulted from radiation exposures in nuclear facilities is quite limited. Excess risk of this disease has been more consistently reported in association with exposure to solvents and oil mists and with metal machining operations [Thomas and Waxweiler, 1986].

The relationship of radiation dose to mortality from brain cancer was examined earlier in a case-control study of workers at Y-12 and Oak Ridge National Laboratory [Carpenter et al., 1987]. Mortality from brain cancer was increased among workers with internal lung doses of 0.15–0.44 Sv, but not among those with higher internal doses, or in relation to external radiation dose. The study was hampered by the small number of brain cancer cases, many of whom lacked data on radiation dose. The same study also yielded some evidence that brain cancer mortality at the two facilities is associated with mercury, beryllium, cutting oils, and solvents, using subjective, semiquantitative exposure scores developed by an occupational hygienist [Carpenter et al., 1988]. Since metal machining, which potentially involves oils and solvents, in addition to metal dusts, was one of the principal activities at Y-12, any future investigation of brain cancer at the plant should include further assessment of these exposures. The mortality study of Y-12 workers exposed to mercury also suggested excess brain cancer deaths were associated with exposure to that agent [Cragle et al., 1984].

Excesses of multiple myeloma, which is included here in the aggregate category of "other lymphatic cancers," have also been observed among nuclear workers, as well as in populations with higher radiation doses [BEIR Committee, 1990], and experimental evidence suggests that bone marrow cancers in general might be associated with internal alpha radiation exposures [BEIR Committee, 1988]. There were 9 deaths from multiple myeloma among the 8,116 Y-12 workers employed after 1947 exclusively, and 17 among the cohort of 10,597 workers that included those who had also worked at the earlier enrichment plant on the site. However, mortality rates for multiple myeloma are not available for the national population for the calendar period in question, so we could not formally examine this tumor separately from the others with which it is grouped. Neither other lymphosarcomas nor non-Hodgkin's lymphoma has been strongly linked to occupational radiation exposure at contemporary levels [BEIR Committee, 1990]. The epidemiological evidence concerning the relationship of multiple myeloma and the lymphomas to other occupational agents is sparse [Savitz and Pearce, 1987].

Mortality from cancer of the kidney, prostate, and pancreas was also elevated among white men at Y-12. However, the epidemiological evidence that cancers of the prostate and pancreas are caused by ionizing radiation is equivocal, at best [BEIR Committee, 1990]. Recent evidence suggests that ionizing radiation can cause kidney cancer, but existing data are not adequate to indicate the doses at which it does so [BEIR Committee, 1990]. Internally deposited uranium may have nephrotoxic effects, associated principally with soluble compounds that were rare at Y-12 [BEIR Committee, 1988]. This is consistent with the absence of excess mortality from chronic nephritis at Y-12. Other occupational agents are associated with these cancers, but none appear to be strongly linked with them. The occurrence of prostate cancer may be elevated among metal workers [van der Gulden et al., 1992], although possibly through exposure to cadmium [Ernster et al., 1979]. Prostate and kidney cancer may also be associated with exposures to some petroleum-based compounds [Wong and Raabe, 1989], and there is evidence that pancreatic cancer is associated with some solvents, as well [Lin and Kessler, 1981]. A modest excess of kidney cancer was reported among Y-12 workers exposed to mercury [Cragle et al., 1984].

The small, mostly African-American cohort of non-white men employed at Y-12 had more favorable mortality experience than the national non-white population when all causes of death and all cancers were considered. An excess of gastrointestinal system cancers was observed, but the number of deaths from this and other specific causes was very small.

Women employed at Y-12 also had considerably lower mortality from cancer and other causes than U.S. women in general during the same time interval. Low mortality among these female workers may be due to underascertainment of deaths, since the vital status of 12% was unknown at the end of follow-up, and death certificates could not be found for 15% of women with death indications. Because of name changes accompanying marriage and divorce, follow-up and death certificate retrieval are often less complete for women than for men. There is no reason to suspect that the underascertainment is differential by cause of death or exposure status, however. There was evidence of an excess of breast cancer among female Y-12 workers, but the number of deaths from other specific causes was too small for analysis.

In contrast to white men, neither women nor non-white men who worked at Y-12 experienced excess mortality from lung cancer or the other cancers discussed above for white men. Women and non-white men may have been placed in different jobs than white men and may consequently have had different exposures, particularly early in the plant's history. From the end of World War II until the 1970s, most women were engaged in clerical and support activities, although they have occupied a broader range of jobs in more recent years.

The finding of excess breast cancer mortality among female workers is noteworthy in light of the widely documented relationship between this disease and exposure to external penetrating radiation [BEIR Committee, 1990]. Few other occupational agents are thought to be causes of breast cancer, although there is growing evidence that electromagnetic fields may be involved [Loomis et al., 1994; John and Gammon, 1993]. We could not examine breast cancer mortality in relation to radiation doses or other occupational exposures, but such relationships would merit further investigation among female nuclear workers. However, because of the modest number of women employed at Y-12, a study of this facility alone would be of limited value.

A roughly three-fold excess of deaths attributed to "symptoms, senility and ill-defined conditions" (ICD-8 780–799) was observed among Y-12 workers, confined largely to white men. This phenomenon is characteristic of cohorts employed at all Oak Ridge installations [Wing et al., 1991; Frome et al., 1990], and appears to be a function of death certification practices in Tennessee [Cragle and Fetcher, 1992].

CONCLUSIONS

Lung cancer mortality merits continued surveillance among Y-12 workers because of temporal patterns of risk suggesting that some exposure which was most intense in the first decade of the plant's operation may have increased the risk of this disease. Ionizing radiation is clearly of concern because of the well-established link between internal alpha radiation exposure and the development of lung cancer. However, nonradiological exposures, beryllium in particular, should be also considered in future studies of lung cancer among this population. Neither the patterns of risk we observed nor the association of lung cancer with radiation exposures in previous studies of this and other populations [Checkoway et al., 1988; Beir Committee, 1988] rule out a role for such agents.

Despite the relatively small numbers of deaths from cancers at sites other than the lung, the findings of elevated mortality from brain cancer, lymphatic cancers other than classified leukemias and lymphomas, and cancers of the pancreas, prostate, and kidney among white men, and of excess breast cancer among women, also merit further investigation. Radiological exposures are again of clear concern, but the epidemiological literature suggests that solvents, electromagnetic fields, and other agents are also worthy of investigation.

While the potential effects of exposure to chemical agents used at Y-12 merit further investigation as part of a comprehensive study of the health consequences of the national nuclear weapons program, there was little evidence of excess mortality from noncancer causes among this population.

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